Distribution of Fluences versus Peak Fluxes and the Cosmological Density Evolution of the Rate of GRBs

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Abstract.
We argue that recent observations of afterglows and some theoretical considerations indicate that the gamma-ray fluence may be a better measure of strength of a burst than its peak flux. We discuss how the distribution of the fluence, or any physical quantity related to the peak counts (or flux), can be obtained with proper correction for threshhold effects. Using this method, we compare the cumulative and differential distributions of flux and fluence. We find some differences between these distributions, but more remarkable are the similarities between these distributions. The other striking feature is how different these distributions are from those of other extragalactic objects. Using the fluence distributions, we derive the expected comoving density rate evolution for different assumed total luminosity; we compare this with the GRB rate expected from the recently determined star formation rate.

INTRODUCTION

In the absence of knowledge of redshifts or direct distances to a large number of gamma-ray bursts (GRBs), we have to rely on the distributions of important physical parameters such as flux, fluence, duration and spectral characteristics, as well as the correlations between these parameters, for further insight into the physics of the energization and radiation of these sources. One approach is to start with specific parametrized models and compare the expected results with observations. Inclusion of all observational constraints makes such models very complex. An alternative approach (the one we prefer until more redshifts are known) is to work from the observations to obtain bias free, non-parametric distributions.

As the name "gamma ray burst" implies, the peak gamma-ray flux f_p of a GRB far exceeds the peak fluxes at other energies. The recent X-ray, optical and radio observations of the afterglows - in particular the fact that these fluxes decline more rapidly than $1/t$ (see e.g. Van Paradijis in these proceedings) - indicate that the

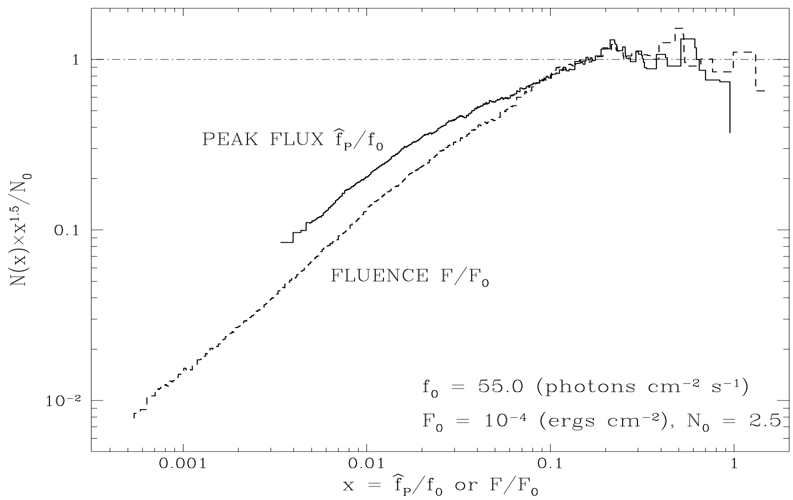

FIGURE 1. The cumulative counts multiplied by the 3/2 power of the variable to remove the Euclidean (more correctly HISE) dependence for fluxes (solid histogram) and fluences (dashed histogram) of the 3B GRBs.

energy fluence F in the gamma-ray range is also higher than in any other band. Therefore, the gamma-ray fluence F provides the best measure of the strength of the burst. This is also what is expected theoretically from the fireball model, where the total radiant luminosity is expected to be a standard candle, representing the released graviational potential, whereas the peak luminosity, duration, etc. (which are affected by the variable values of the bulk Lorentz factor or baryon loading of the fireball) are not expected to be standard measures.

In spite of this, most analysis such as the Log$N$-Log$S$, time dilation, etc. have been carried out using the peak photon flux with the tacit assumption that the peak photon luminosity is a representative measure of the burst strength. The primary reason for this is because the burst triggering is based on photon counts (or flux) and not on the fluence. However, this should not deter us from using the fluences because, as argued by Petrosian and Lee [1], the existing data can be used to determine the limits on the fluences of the bursts. In fact, this argument can be generalized to any physical quantity X related to the parameter which determines the triggering threshold, which is, in this case, the peak flux f_p or the peak count $C_{\max}$. For example, given f_p, its threshold f_{lim} and the relation $X(f_p)$, then in the spirit of the well known V/V_{max} test, we can ask: What is the range of possible values of X so that the peak flux exceeds the threshold? The limiting values $X_{\min}$ and/or $X_{\max}$ are obtained from $X(f_{lim})$.

Quantities related to the flux monotonically, e.g. fluence, will have only a lower limit while those with a more complex relation may have both an upper and a lower bound. In our past works in this area we have developed and utilized non-parametric methods to determine the bias free distributions and correlations from data truncated on one side [2,3]. We have recently generalised these to the two

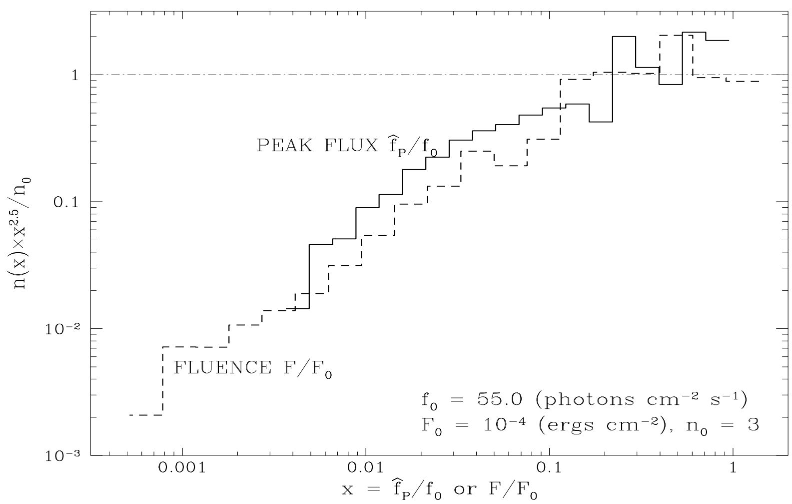

FIGURE 2. The differential counts multiplied by the 5/2 power of the variable to remove the Euclidean (more correctly HISE) dependence for fluxes (solid histogram) and fluences (dashed histogram) of the 3B GRBs.

sided truncation case [4]. An example of such a case is discussed by us elsewhere in these proceedings [5], dealing with the distribution of the peak energy E_p of thr $\nu F(\nu)$ spectrum. Here we use the one sided methods and compare the distributions of the flux and fluence.

DISTRIBUTIONS OF FLUX AND FLUENCE

Figure 1 shows the cumulative distributions of peak fluxes and fluences of the GRBs in the 3B catalog, where the bias at low values of these quantities due to the threshold and the effects of correlations have been corrected for. For details the reader is refered to our earlier papers [1,2,6]. We plot the deviations from the -3/2 power law dependence expected in the homogeneous, isotropic, static and Euclidean (HISE) model.

For both quantities there are well defined 3/2 power law portions and a sharp deviation from this, especially for the fluence. This may be an indication that the total luminosity has a narrower distribution (is a better standard candle) than the peak luminosity. This and the larger range of the fluence makes it a more appropriate parameter for cosmological tests.

The differential distributions divided by that expected for HISE case are shown in Figure 2. The above mentioned difference is evident here, although to a lesser degree. A more striking feature is the remarkable similarity between the shapes of the two distributions. These differences and similarities can be also seen in Figure 3.

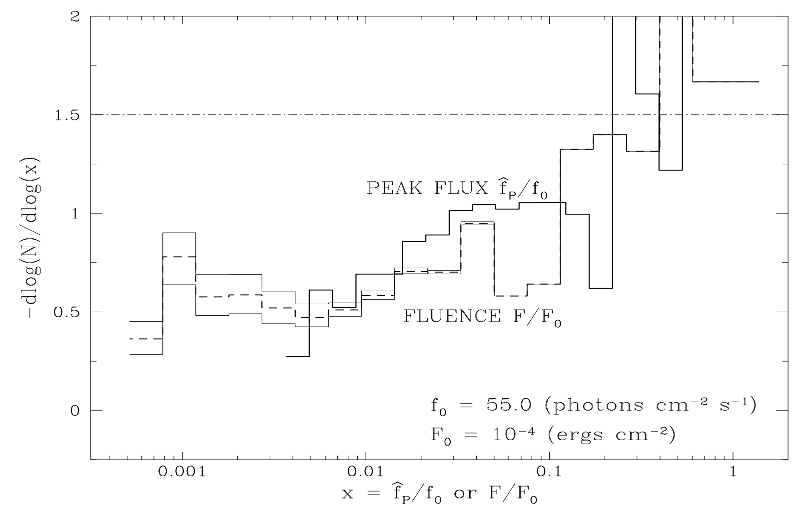

FIGURE 3. The logarithmic slope of the cumulative counts for fluxes (solid histogram) and fluences (dashed histogram) of the 3B GRBs. The thin solid lines show the 90% confidence limits on the corrections used for the threshold and correlation effects (1)

RATE EVOLUTION AND DISCUSSION

The above counts are unlike the counts of other well known extragalactic sources such as galaxies, radio sources and AGNs or quasars. The transition from 3/2 power law is too abrupt and the slope beyond this transition is nearly constant, especially for the fluence. Clearly, some extraordinary evolutionary processes are at work. There has been several detailed analyses of the distributions of the fluxes (see e.g. references [7] or [8]) with inconclusive results. This is primarily because any observed distribution can be fitted to an arbitrary luminosity function and evolution even if one assumes a cosmological model. To obtain some indication of possible evolutions, we assume several representative values for the emitted energy or the total luminosities $\mathcal{L}$ and derive the comoving rate density from observed differential counts of the fluences;

$$\rho(z) = (1+z)n(F)(dz/dV)(dF/dz). \tag{1}$$

Here $F = \mathcal{L}\ /(4\pi d_L^2(1+z)^{\beta-3})$; $d_L = (2c/H_0)(1+z-(1+z)^{1/2})$ is the luminosity distance in an $\Omega = 1, \Lambda = 0$ cosomological model, and $-\beta$ is the photon flux spectral index. Figure 4 shows this rate evolution for three representative values of $\mathcal{L}$ and for two spectral indices. For a low energy source $\mathcal{L} = 10^{51}$ erg/s, the density decreases with redshift, while it increases for high energies. The observed redshift of 0.83 for GRB 970508 indicates that the most likely energy is about $\mathcal{L} = 10^{52}$ erg/s with possibly little evolution.

Figure 4 also shows the star formation rate from Madau ([9], solid curve), this rate delayed by 2×10^9 years (dashed curve), and the rate convolved with a distribution of delays $P(t) \propto t^{-1}$ (dot-dashed curve; see ref. [10]). As evident, the observed

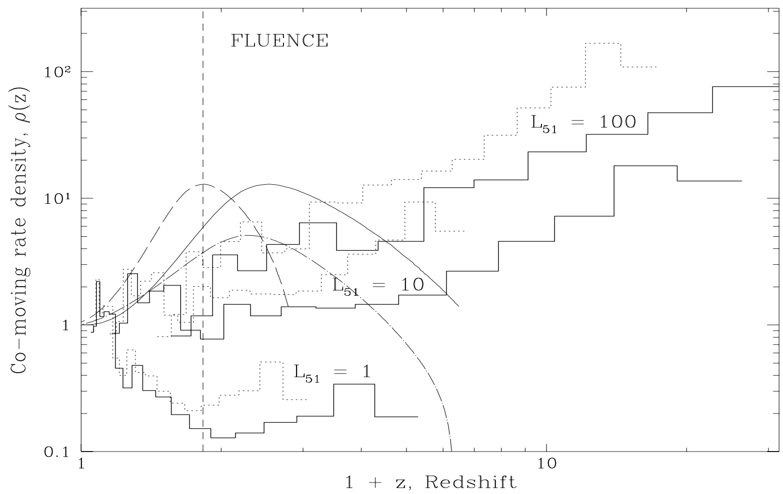

FIGURE 4. Rate per unit co-moving volume of GRBs as a function of redshift obtained from the differential distribution of the fluences for three different energies of GRBs ($L_{51} = \mathcal{L}\ /(10^{51}$ ergs) and two different values of the photon spectral index: $\beta = 2$ (solid histogram), $\beta = 3$ (dotted histogram). The vertical dashed line shows the location of the redshift of the May 8, 1997 afterglow. The continuous curves show three representative rates expected from the star formation rate (see text). $H_o = 60 \mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$.

evolutions are not similiar to that expected from the star formation rate, indicating a complex distribution of $\mathcal{L}$ and the presence of other evolutionary processes.

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